Sources of Variability in Heat Release Rate Measured in the Ohio State University Apparatus

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Background

The U.S. Federal Aviation Administration (FAA) is revising Chapter 25, Section 853 of Title 14 of the Code of Federal Regulations governing flammability of aircraft cabin materials to more closely reflect fire threats (in flight and post crash) and improve the reproducibility of the tests.

Objective

Determine the effect of measurement method (oxygen consumption versus thermopile) and airflow parameters on the reproducibility and repeatability of the heat release rate (HRR) test for Cabin Materials.

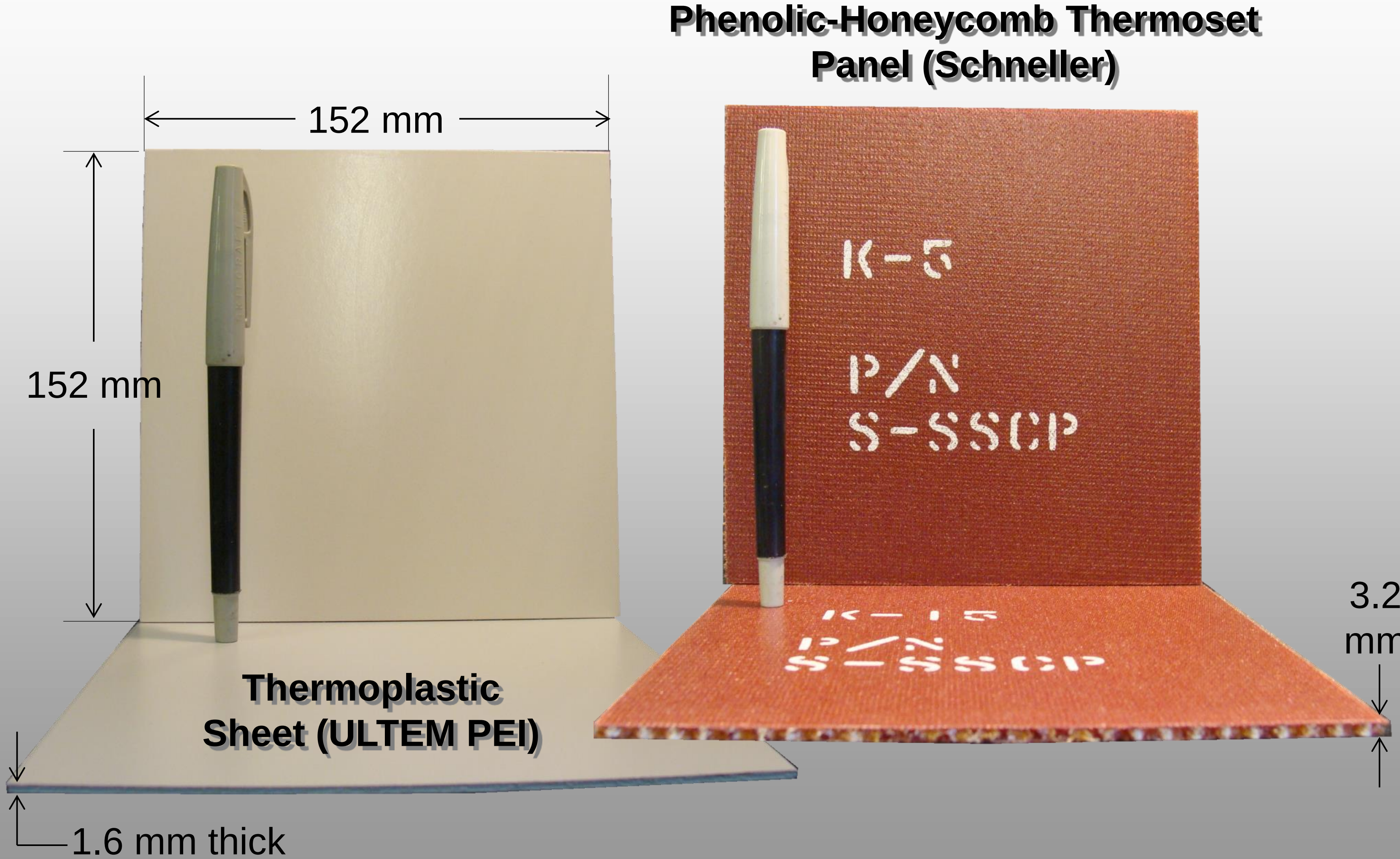
Ohio State University (OSU) Fire Calorimeter is the basis for 14 CFR 28 Section 853 Heat Release Rate Test for Cabin Materials

Heat release rate is measured by sensible enthalpy (temperature rise) of combustion gases

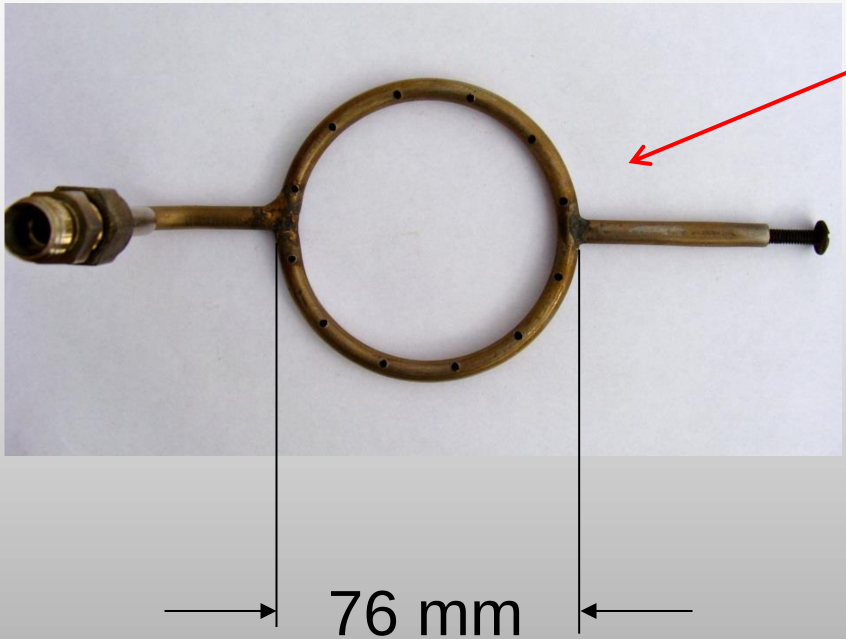
Approach

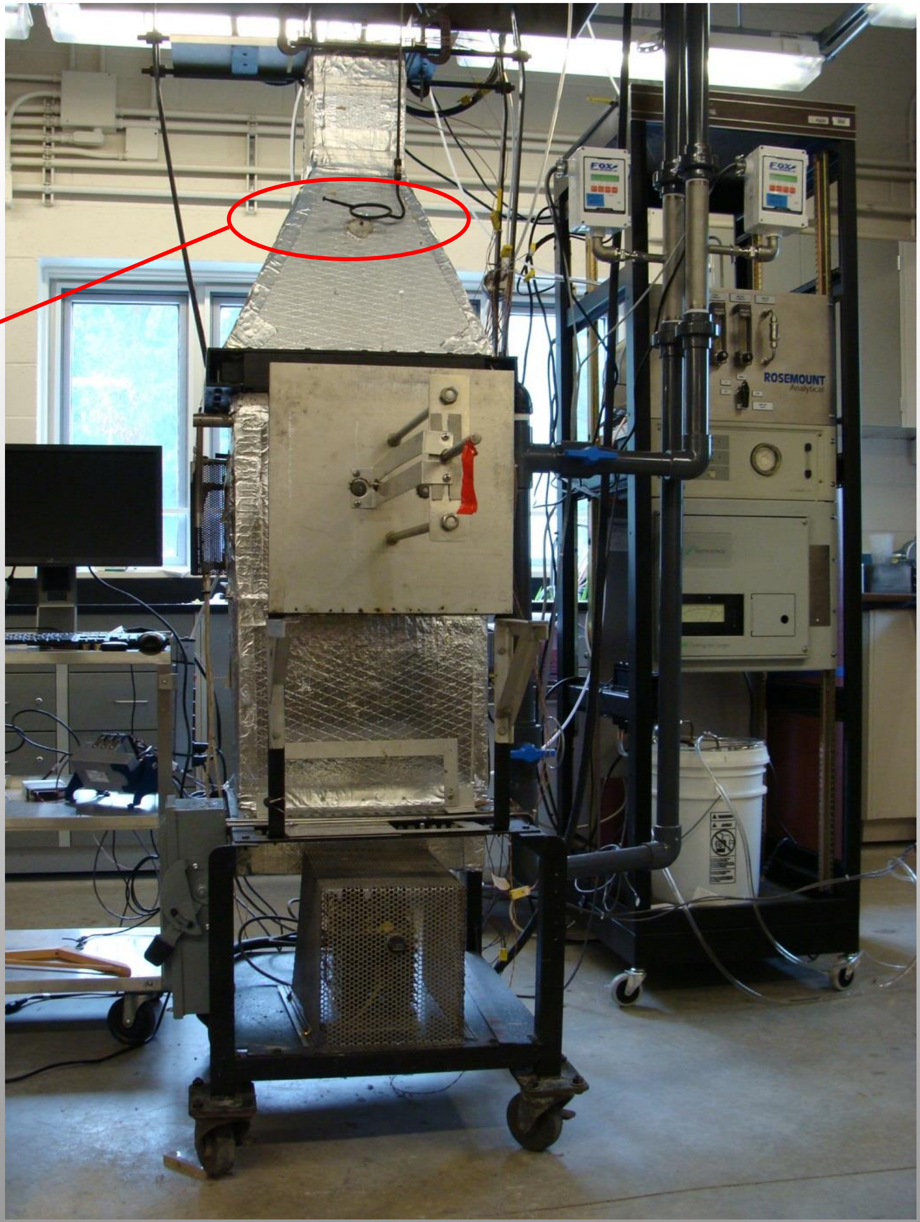
- Identify three (3) 14 CFR compliant OSU fire calorimeters measuring heat release rate (HRR) by the sensible enthalpy/thermopile (TP) method.
- Vary the ratio of bypass airflow to chamber airflow (*s*) at constant total flow rate and measure the effect on calibration factor (k_h) and HRR.
- Develop a portable oxygen consumption measurement (O2) system to calculate HRR from ΔO_2, i.e., convert OSU to O2SU.
- Measure HRR and 2-min heat release (HR) in 3 OSUs for two (2) commercial aircraft materials by O2 and TP methods:
  - Thermoplastic sheet (ULTEM PEI)
  - Thermoset (phenolic) sandwich panel
- Estimate Repeatability and Reproducibility of HRR and HR with regard to:
  - Method of HRR measurement (O2 versus TP)
  - Air flow in test chamber (O2, TP)
  - Apparatus dynamics (TP)

Materials (Typical Aircraft Interior)



Oxygen Consumption System (O2SU)

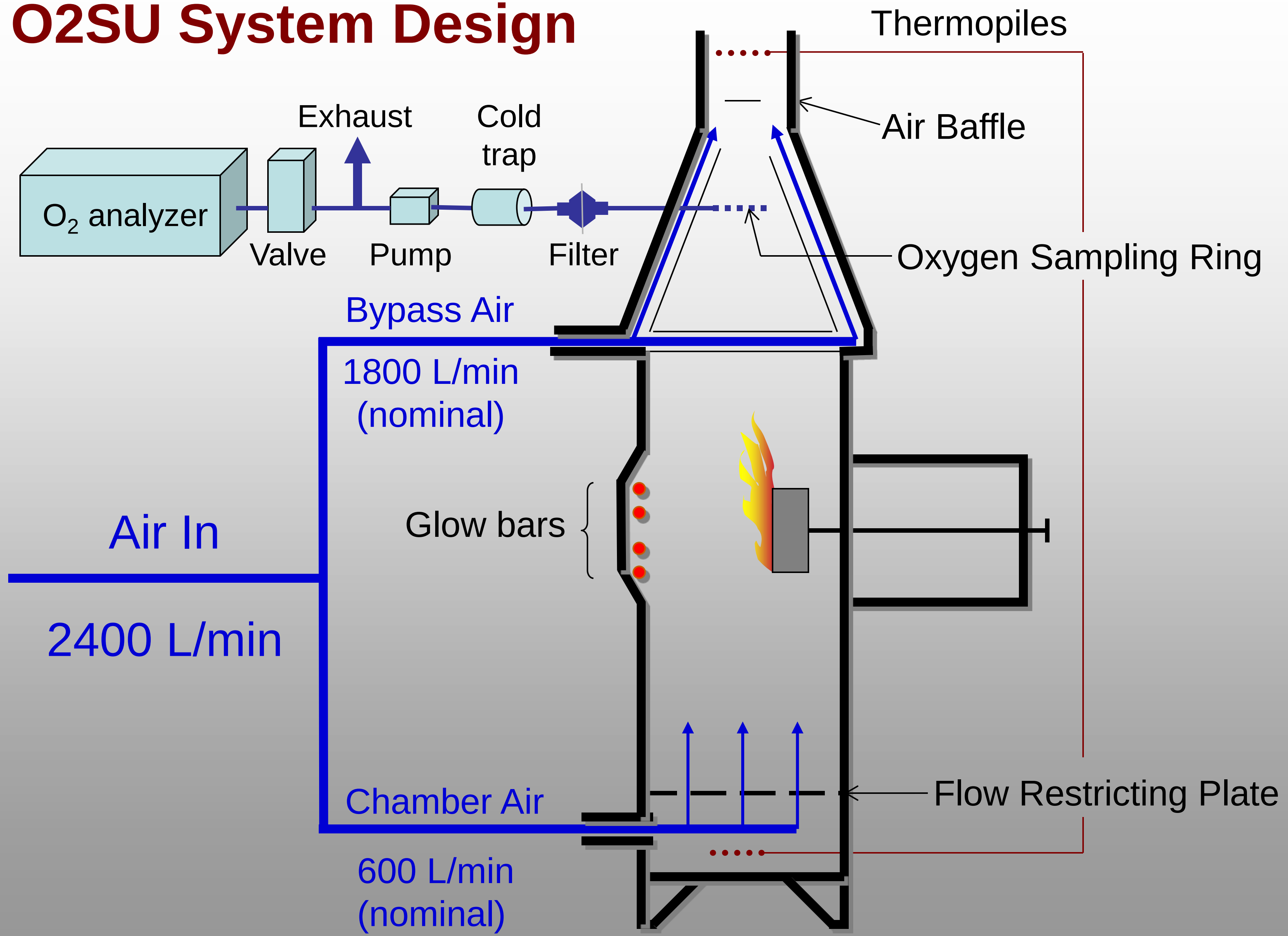




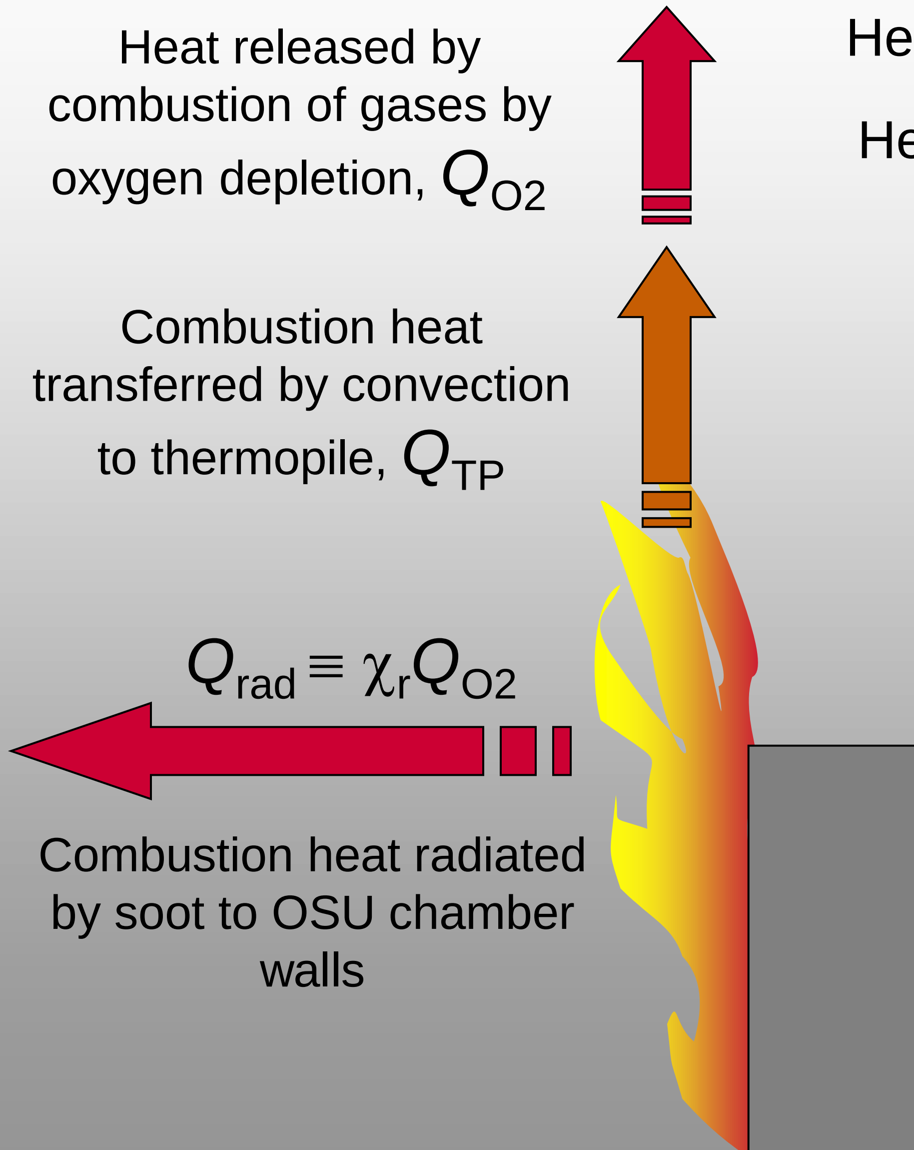
Gas Sampling Ring

- 6.4 mm SS tubing
- 12 holes, 1.6 mm diameter each

O2SU System Design



Energy Balance for Flaming Combustion in OSU



Heat of combustion of sample = Q_0

Heat of combustion of soot = Q_{soot}

$$Q_{O2} = Q_0 - Q_{soot}$$

$$\begin{aligned} Q_{TP} &= Q_{O2} - Q_{rad} \\ &= Q_{O2} - \chi_r Q_{O2} \end{aligned}$$

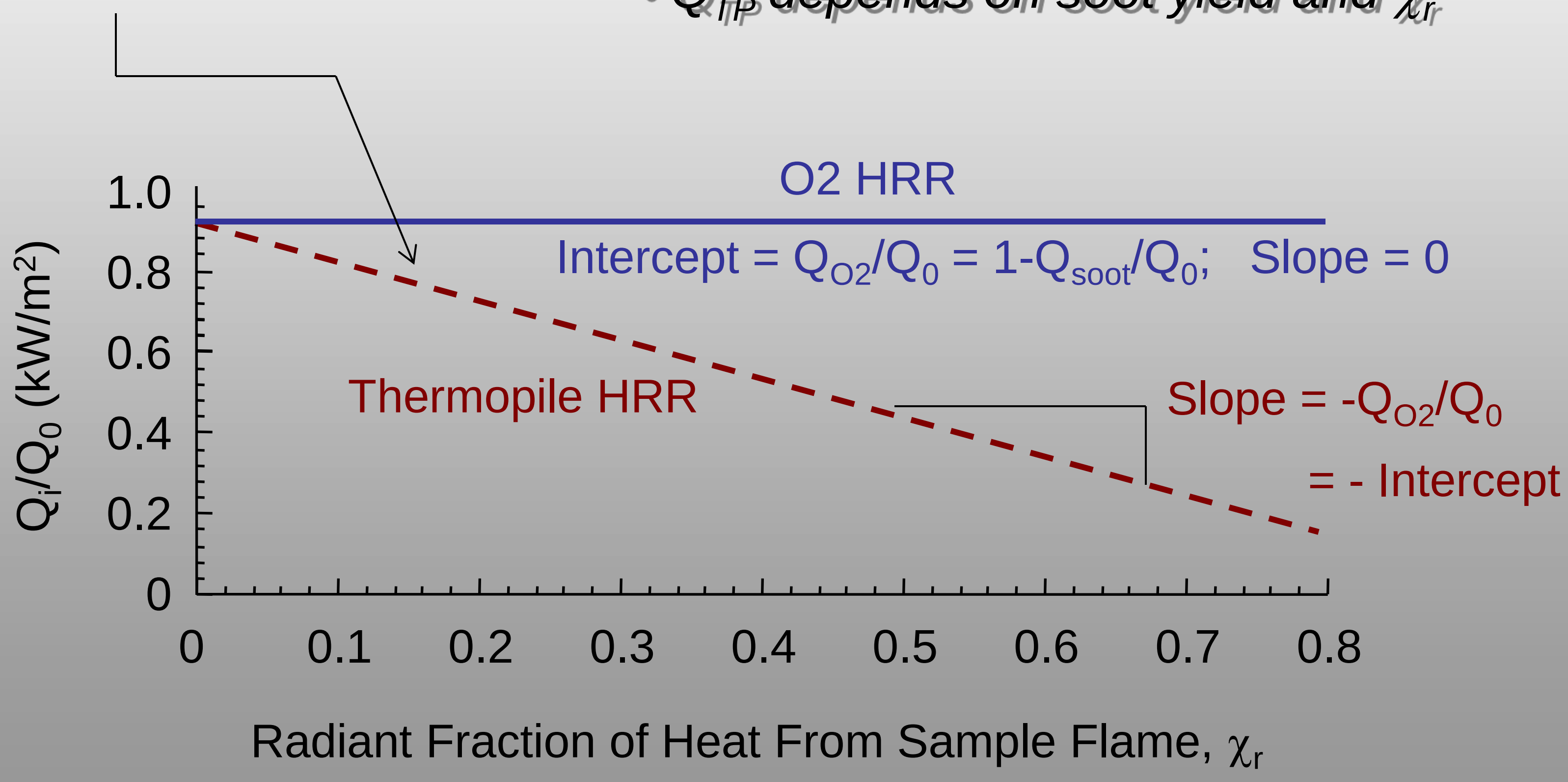
$$\boxed{\frac{Q_{TP}}{Q_0} = \frac{Q_{O2}}{Q_0}\left(1 - \chi_r\right)}$$

Relationship between HRR by TP and O2

Effect of Radiant Fraction of Combustion Heat χ_r on HRR: TP vs O2

$$\frac{Q_{TP}}{Q_0} = \frac{Q_{O2}}{Q_0}(1-\chi_r)$$

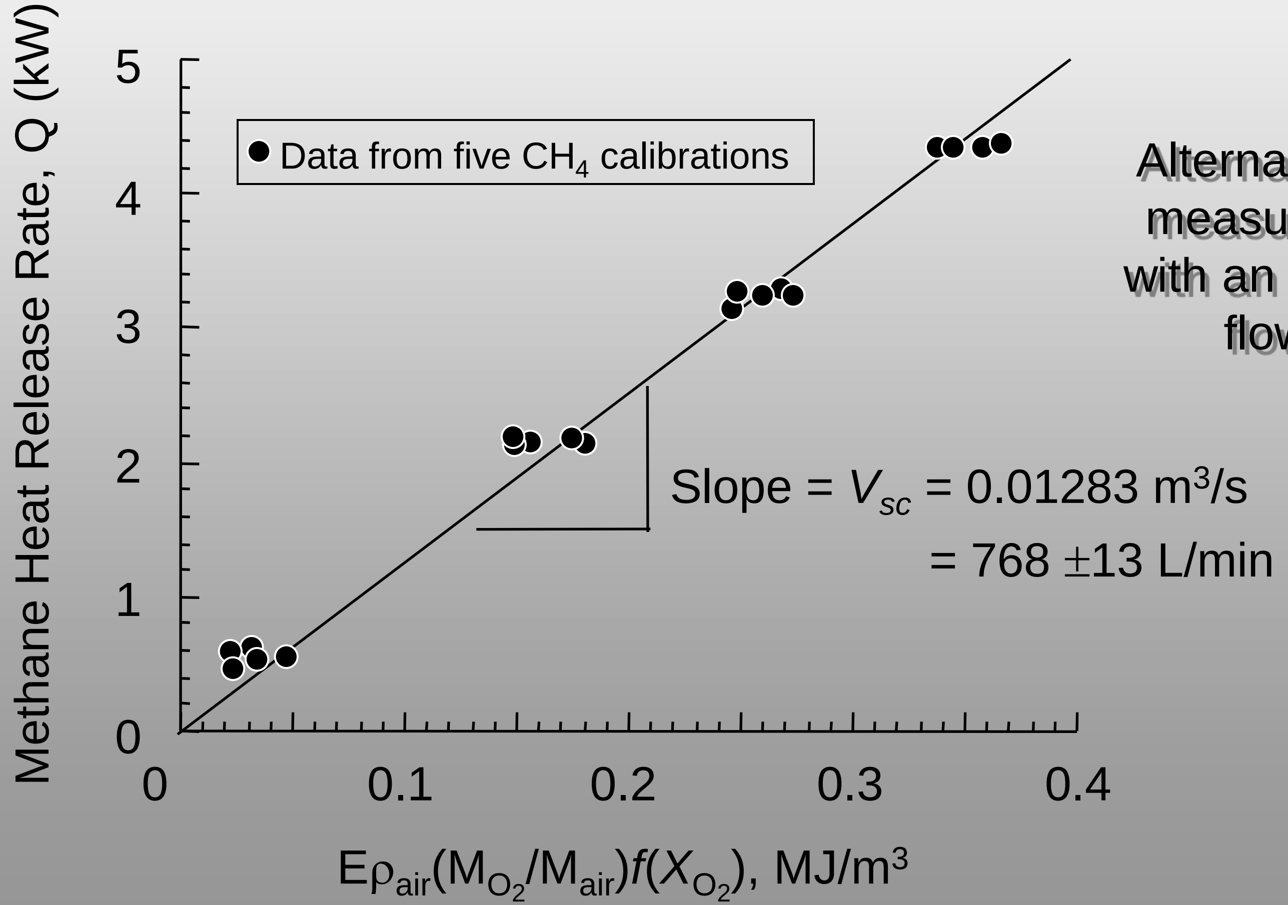
- Q_{O2} depends on soot yield but not on χ_r
- Q_{TP} depends on soot yield and χ_r



Air Flow Rate Through OSU Chamber (V_{sc}) is Needed to Calculate O2 HRR is Obtained from CH_4 Calibrations

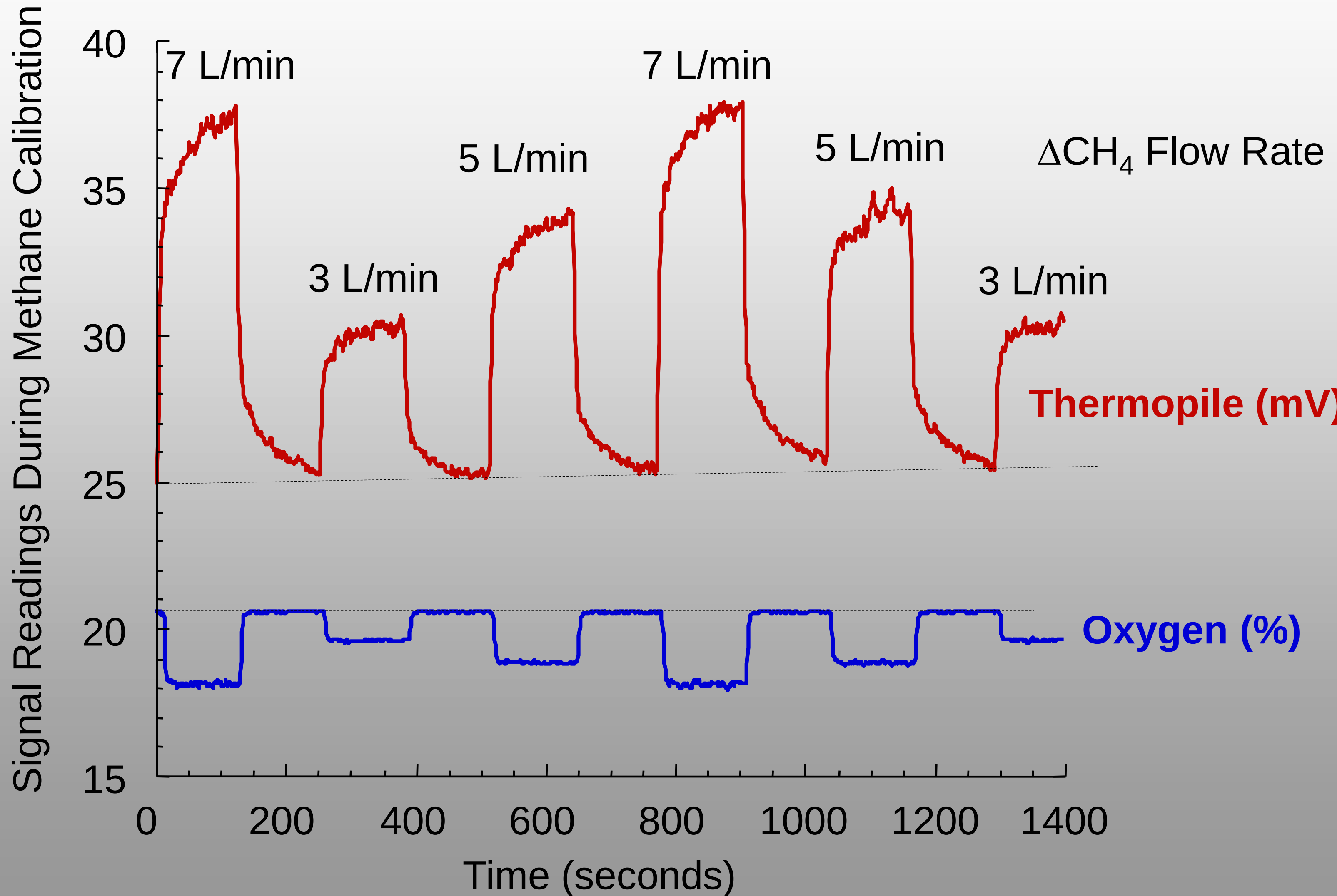
$$Q(W) = V_{sc}\left\{E\rho_{air}\frac{M_{O_2}}{M_{air}}\frac{X_{O_2}^0 - X_{O_2}}{1-X_{O_2}}\right\} = V_{sc}\left\{E\,\rho_{air}\frac{M_{O_2}}{M_{air}}f(X_{O_2})\right\}$$

W.K. Chow and S.S. Hahn, Applied Thermal Engineering 31, 304-310 (2011)



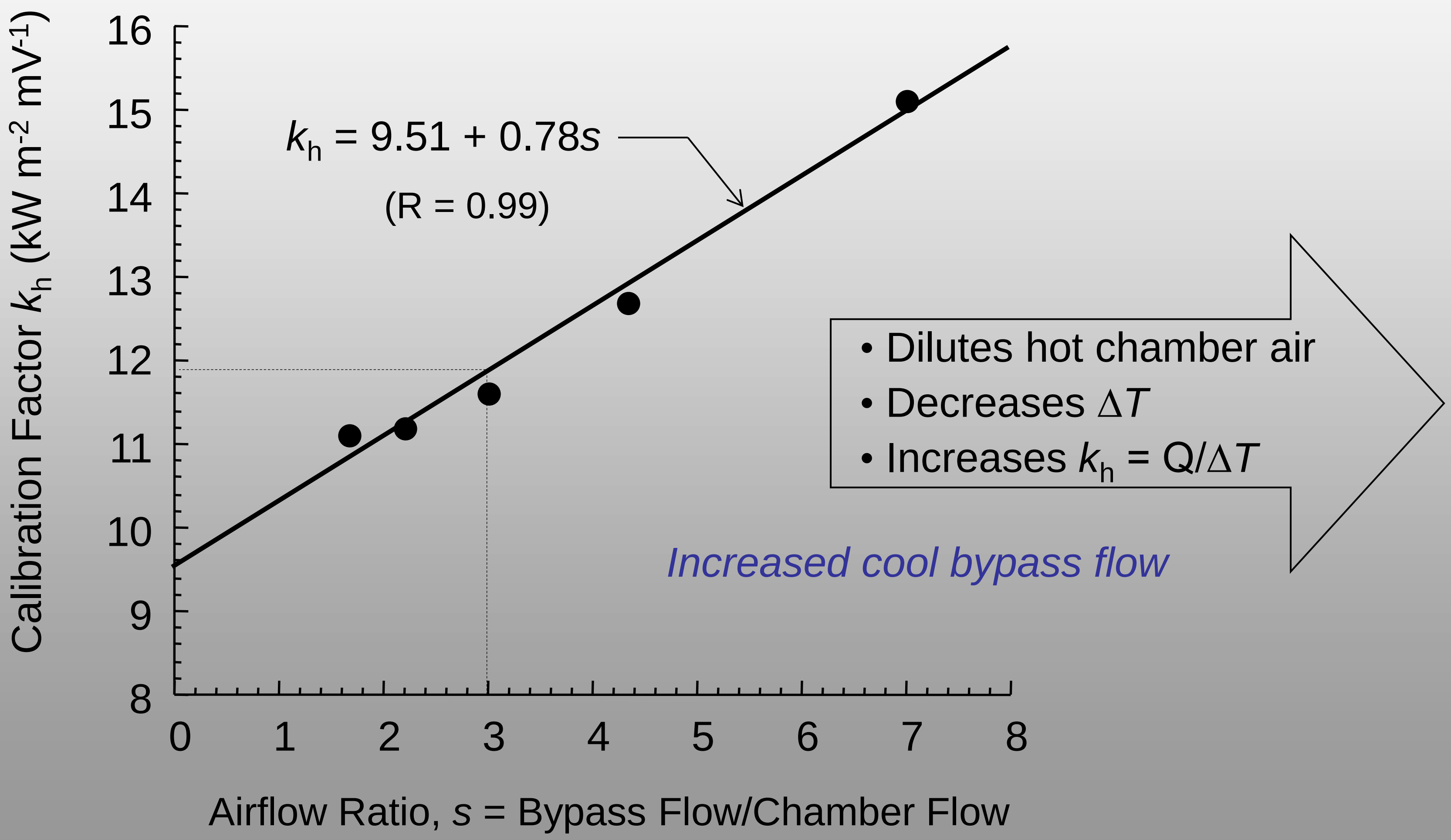
Alternatively, V_{sc} is measured directly with an in-line mass flow meter

Simultaneous O2 and TP Signal Response During Methane Calibration

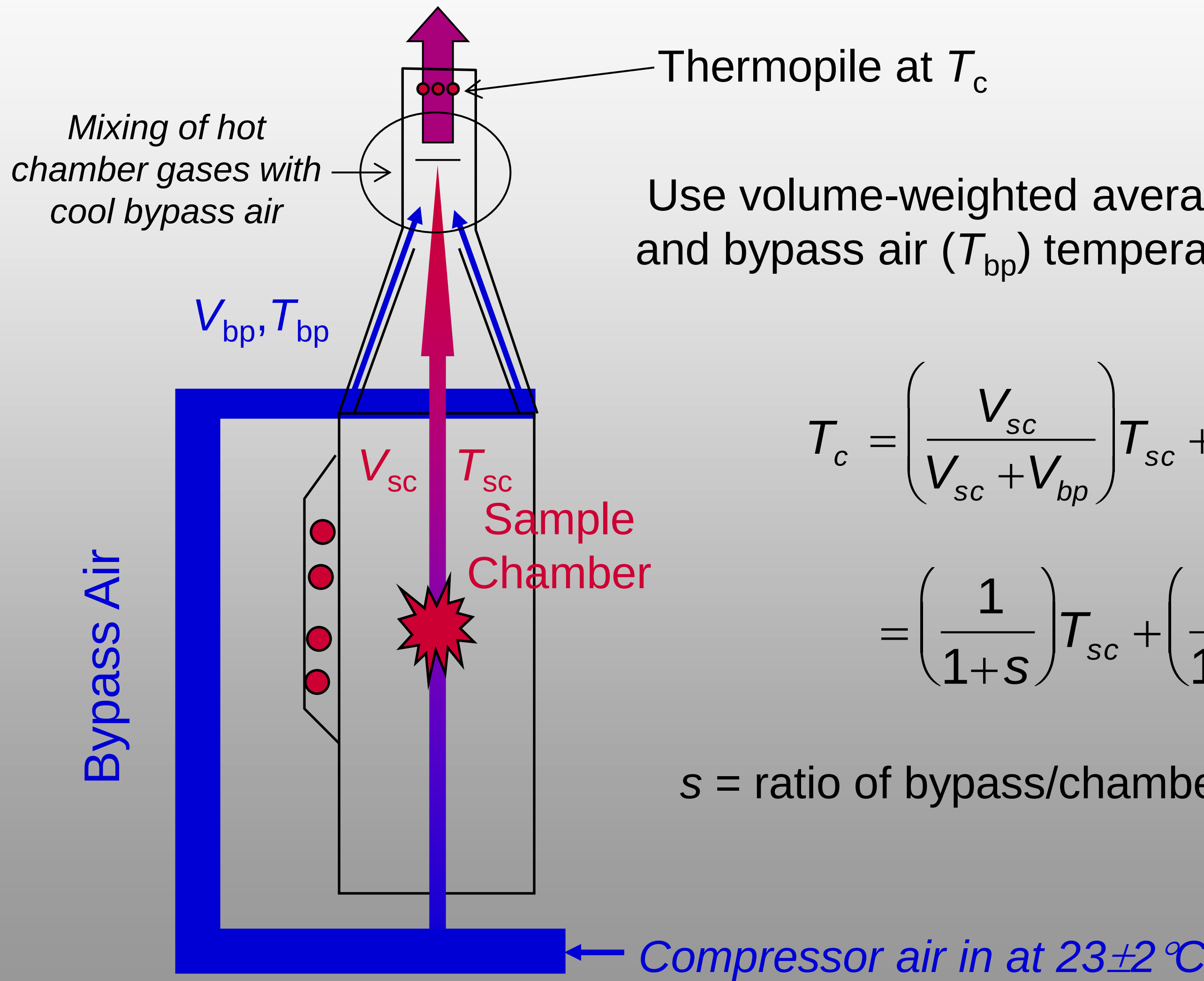


Thermopile (TP) Method:
Effect of Airflow on Calibration Constant

Relative standard deviation < 2% (within specification) for all k_h



Assume Thermopile Reading is Average of Sample Chamber and Bypass Air Temperatures



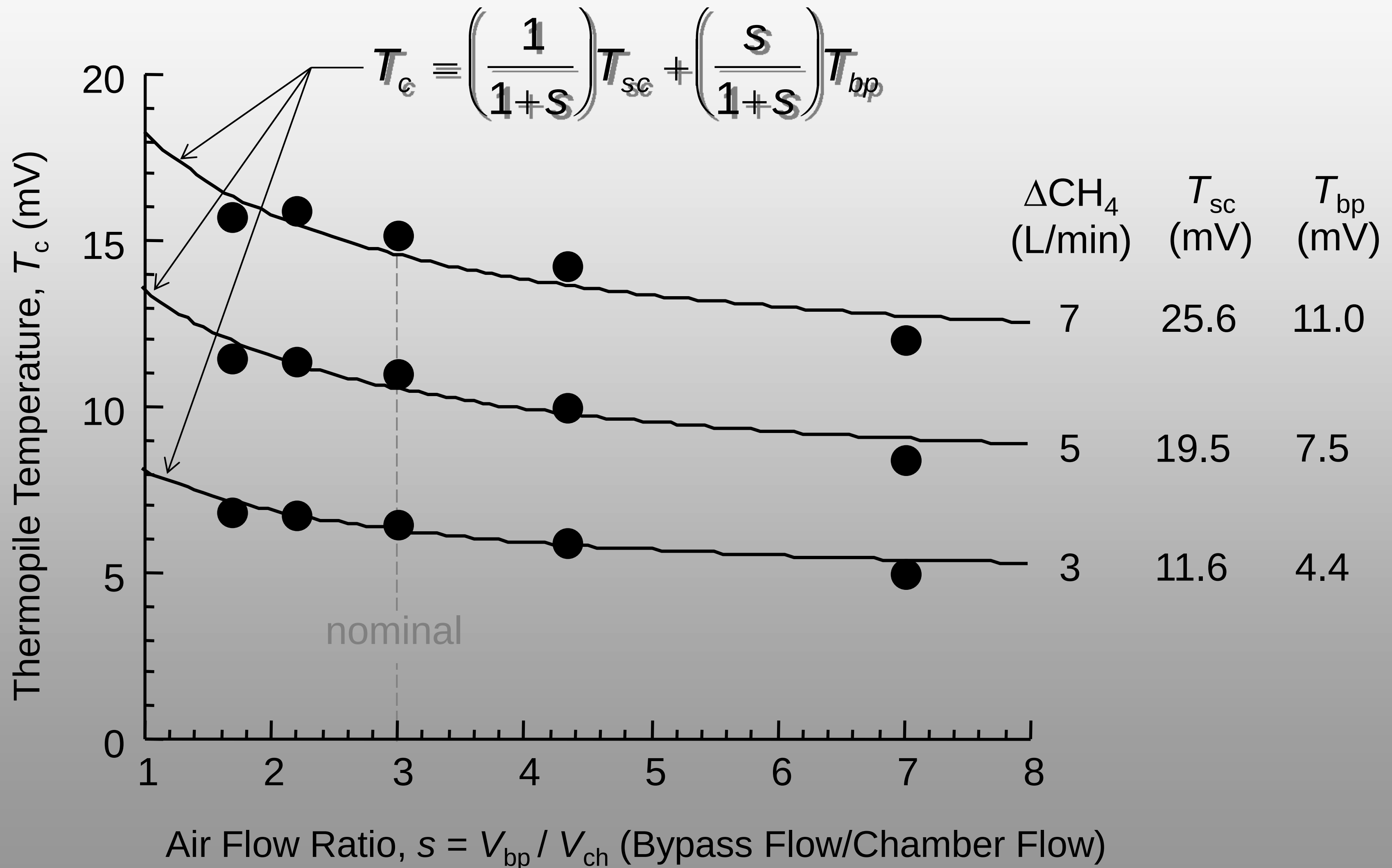
Use volume-weighted average of chamber (T_{sc}) and bypass air (T_{bp}) temperatures to calculate T_c

$$T_c = \left(\frac{V_{sc}}{V_{sc}+V_{bp}}\right)T_{sc} + \left(\frac{V_{bp}}{V_{sc}+V_{bp}}\right)T_{bp}$$

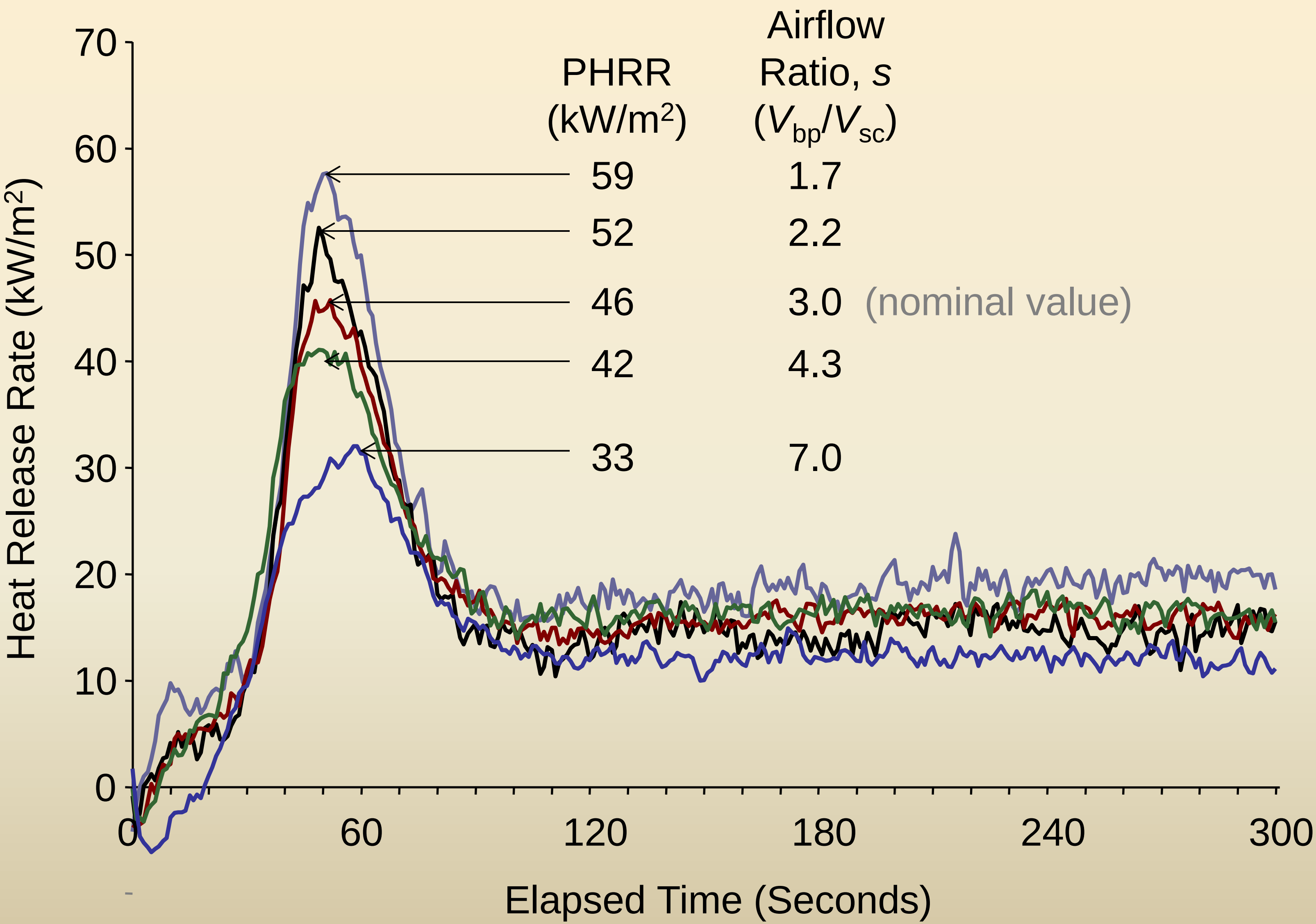
$$= \left(\frac{1}{1+s}\right)T_{sc} + \left(\frac{s}{1+s}\right)T_{bp}$$

s = ratio of bypass/chamber flow rates = V_{bp}/V_{sc}

Temperature Averaging Explains Thermopile Readings for Methane Calibration



Effect of Air Flow Ratio on Heat Release Rate History of Phenolic Panel by Thermopile (TP) Method



Effect of Radiant Heat Transfer on Thermopile HRR

χ_r = Radiant fraction of chemical heat release rate = Q_{rad} / Q_{02}

s = Ratio of bypass airflow (V_{bp}, L/min) to sample chamber airflow (V_{sc}, L/min)

Sample chamber gas temperature depends on convected heat, Q_{TP} radiated heat Q_{rad}, chemical heat Q_{02}, and χ_r

$$T_{sc}(\chi_r) = \frac{Q_{TP}}{k_h} = \frac{Q_{02} - Q_{radiated}}{k_h} = \frac{Q_{02}}{k_h}\left(1 - \frac{Q_{rad}}{Q_{02}}\right) = T_{sc}^{0}(1 - \chi_r)$$

For $T_{sc} = Q_{O2}/k_h$, OSU (TP) Heat Release Rate = $f(\chi_r)$

$$HRR(\chi, s) = k_f(s)T_c(s, \chi_r) = k_f(s)\left\{\frac{s}{1+s}T_{bp} + \frac{(1-\chi_r)}{1+s}T_{sc}^{0}\right\}$$

PHRR Follows Rule of Mixtures for Airflow Temps After Correcting T_{sc} for Radiant Heat Transfer

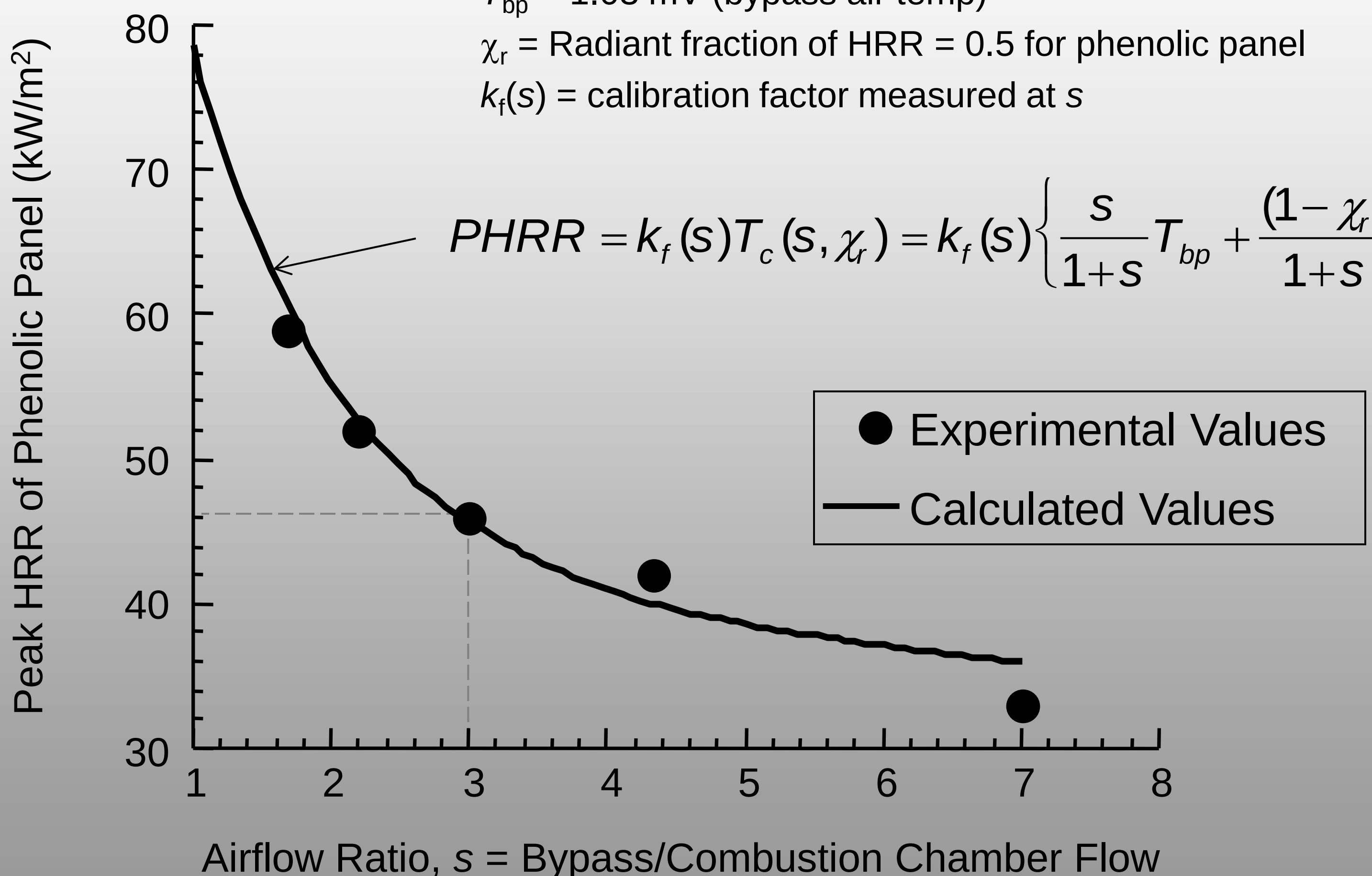
T_{sc}^{0} = 30.4 mV (combustion gas temp for O2)

T_{bp} = 1.03 mV (bypass air temp)

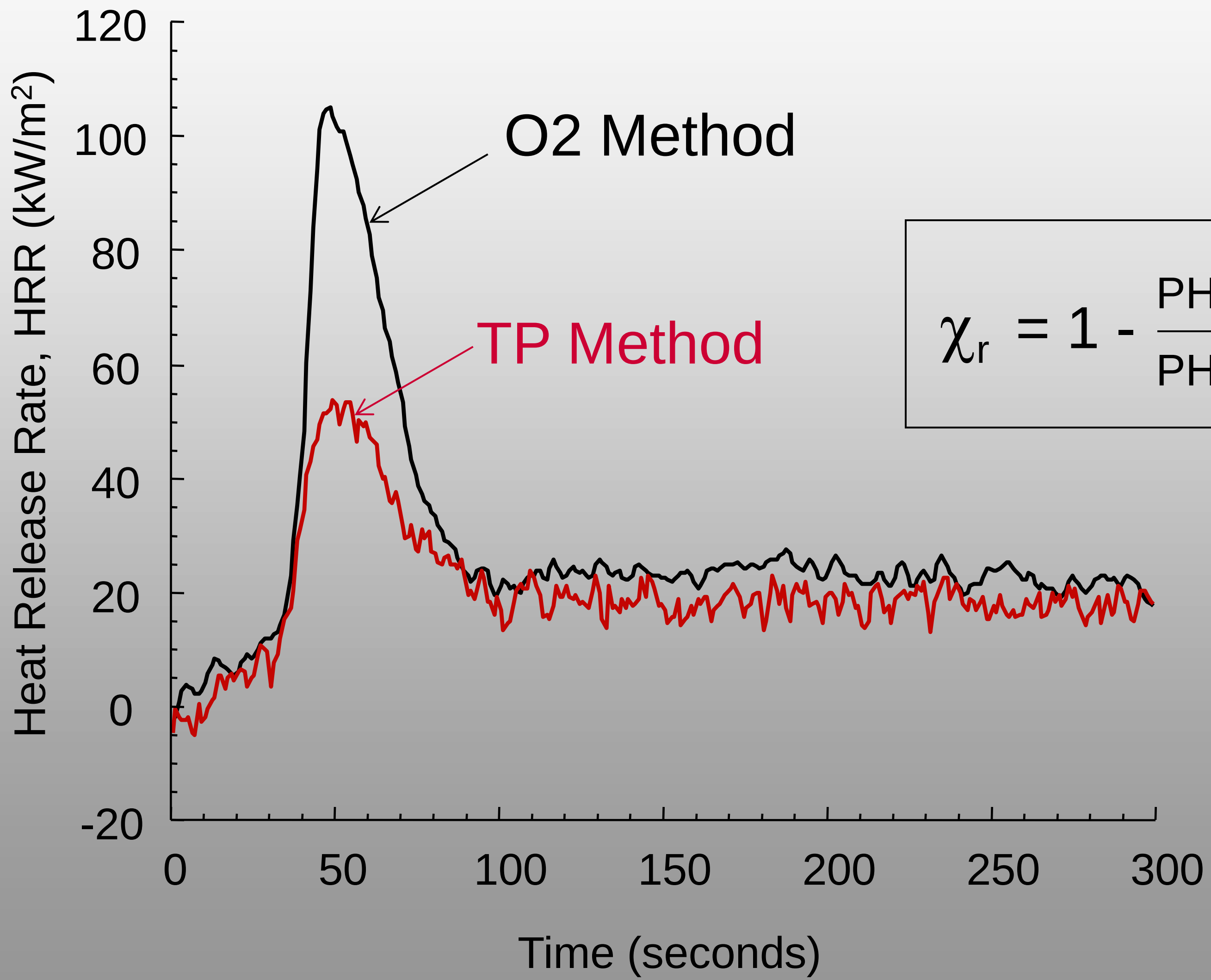
χ_r = Radiant fraction of HRR = 0.5 for phenolic panel

$k_f(s)$ = calibration factor measured at s

$$PHRR = k_f(s)T_c(s,\chi_r) = k_f(s)\left\{\frac{s}{1+s}T_{bp} + \frac{(1-\chi_r)}{1+s}T_{sc}^{0}\right\}$$

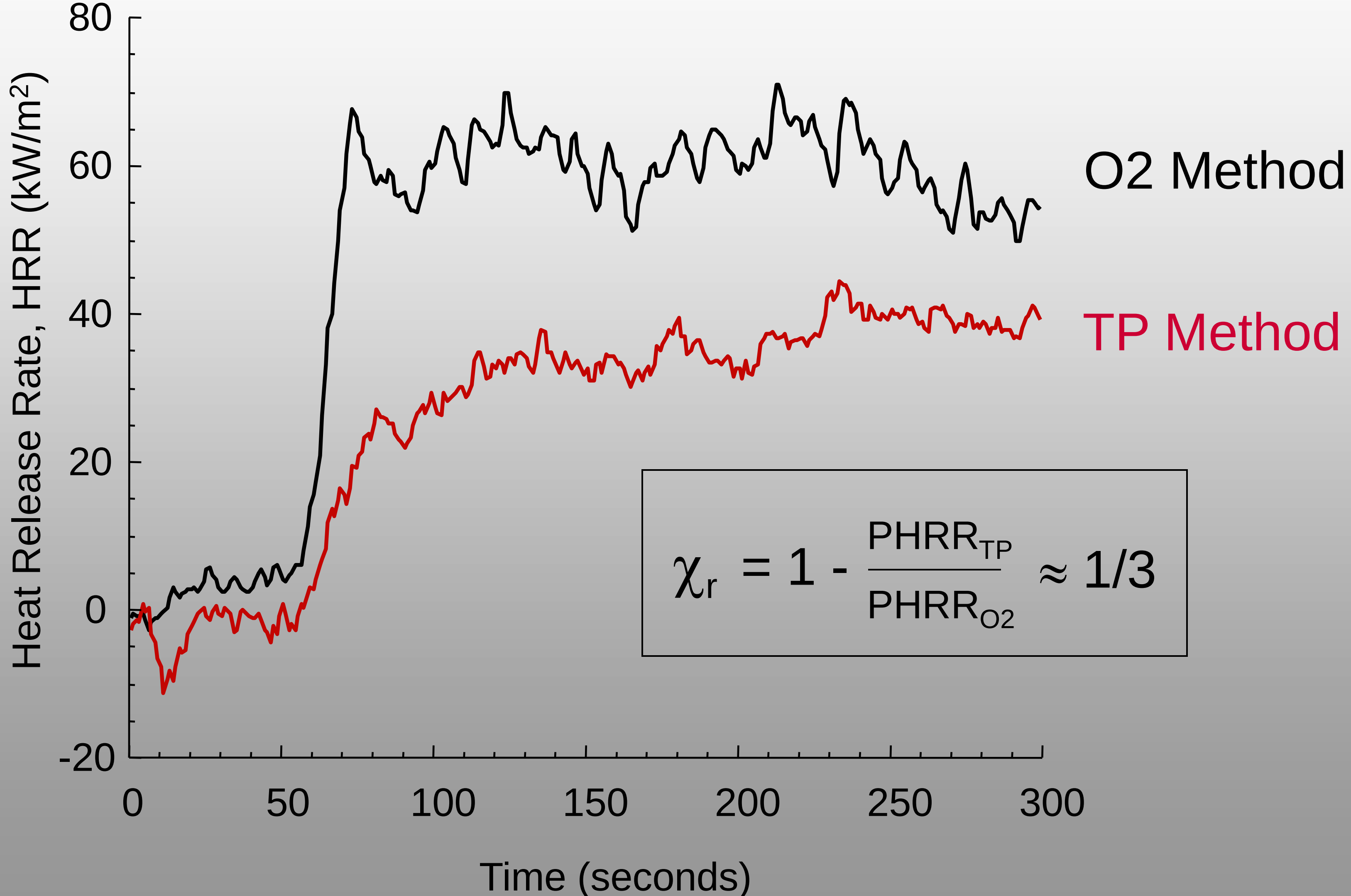


Thermoset Phenolic Panel Test: Simultaneous O2 and TP Measurements

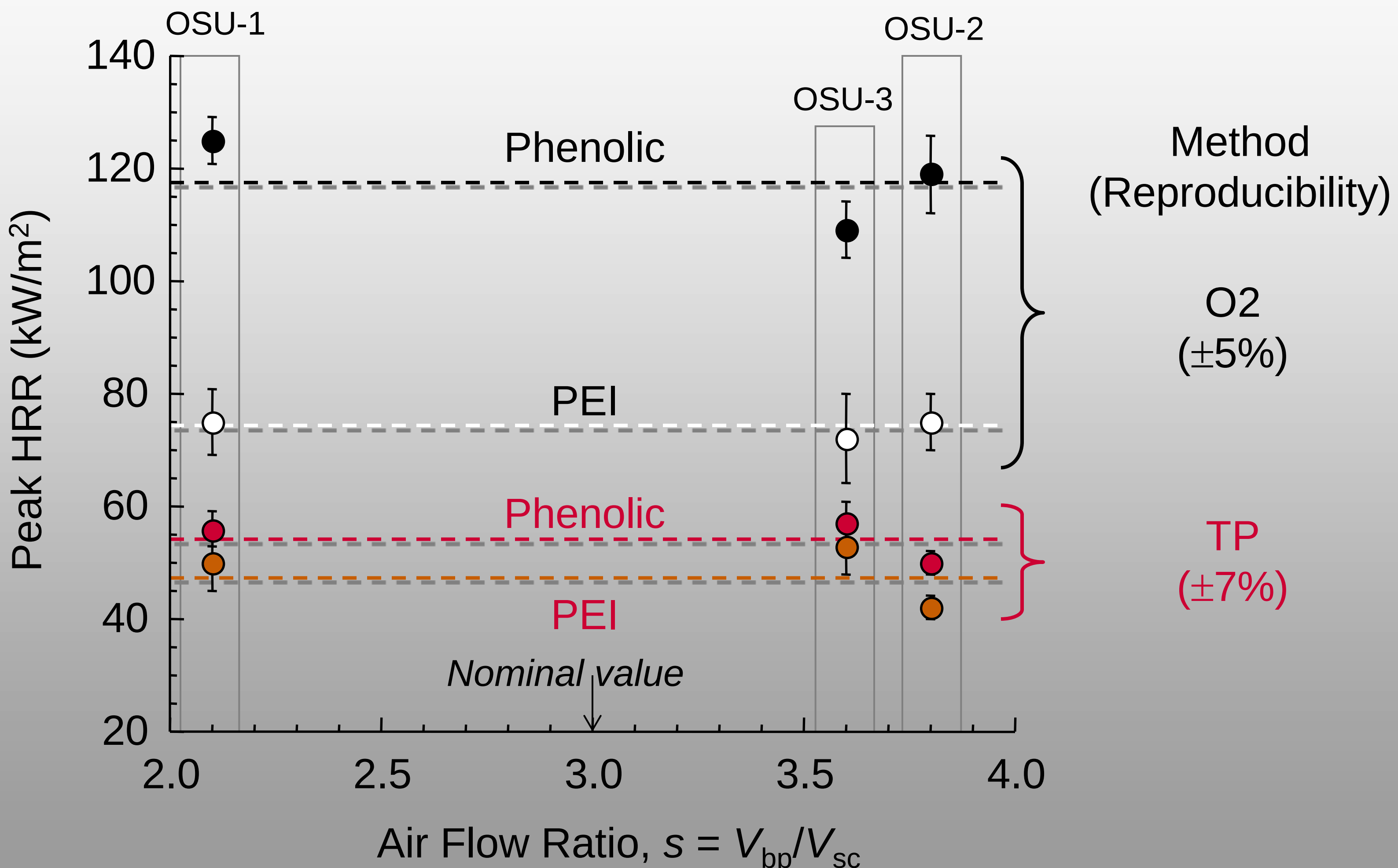


$$\chi_r = 1 - \frac{PHRR_{TP}}{PHRR_{O2}} \approx 1/2$$

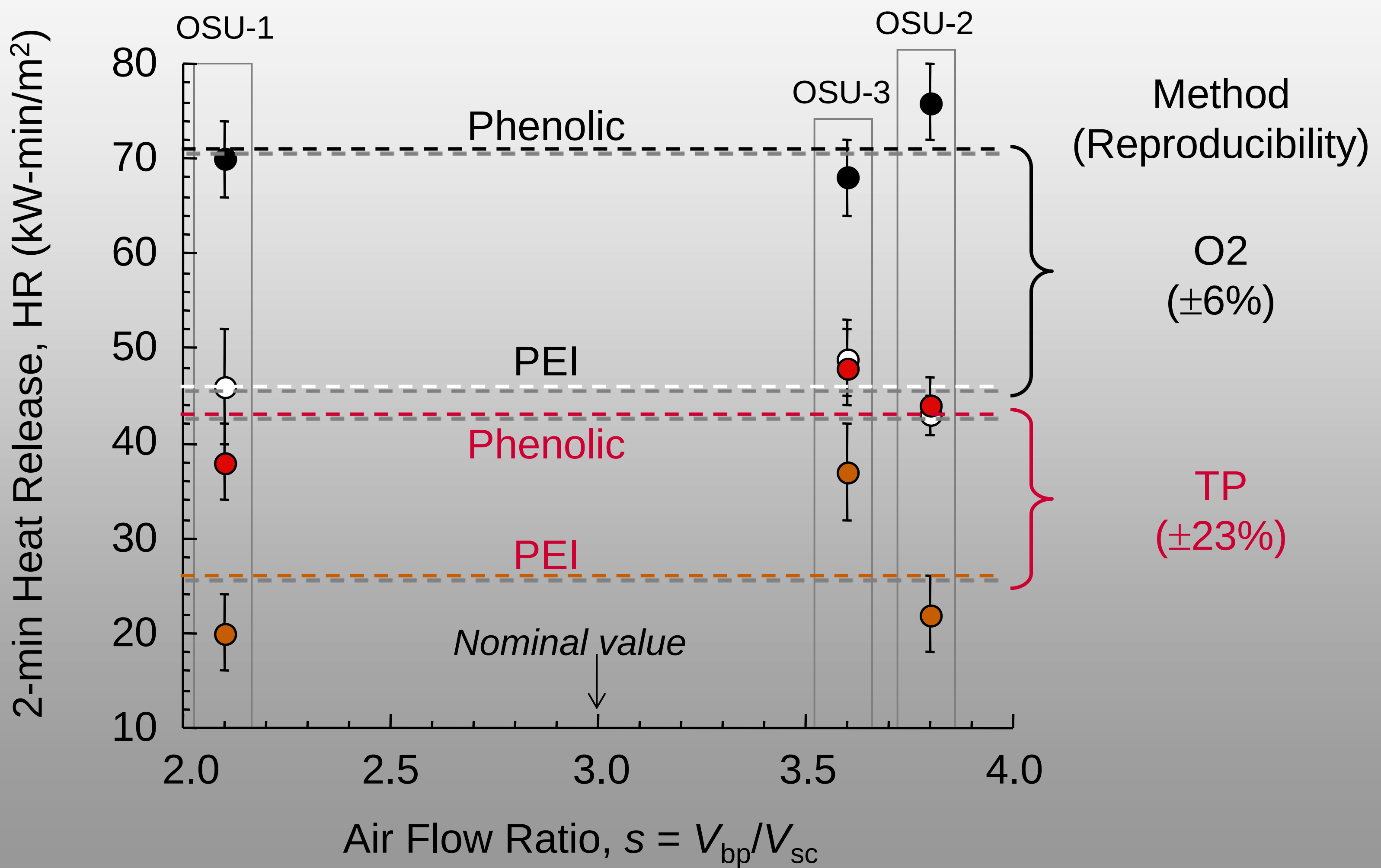
Thermoplastic PEI Sheet Test: Simultaneous O2 and TP Measurements



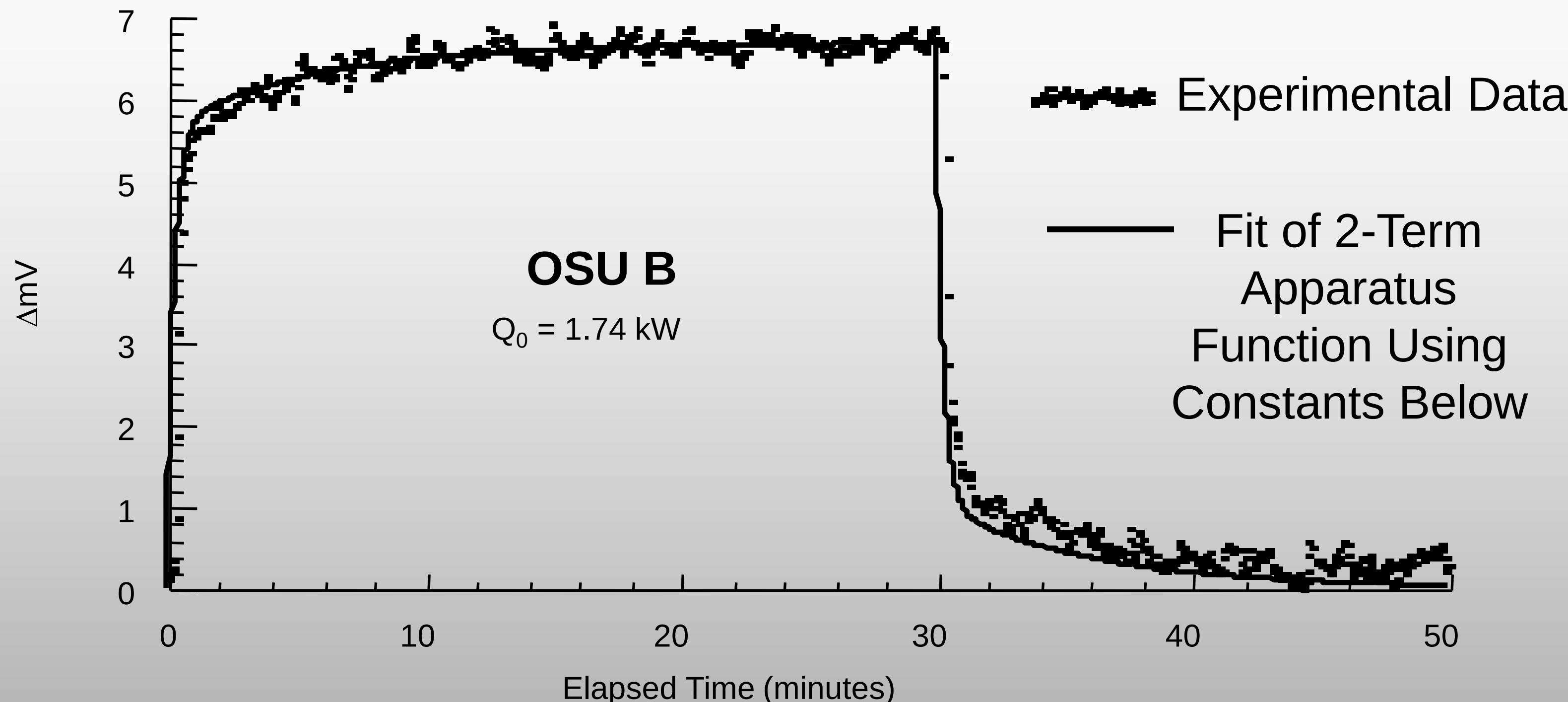
Peak HRR: O2 > TP
Air Flow Ratio: No trend



2-minute HR: O2 > TP
Reproducibility: O2 > TP
Air Flow Ratio: No trend



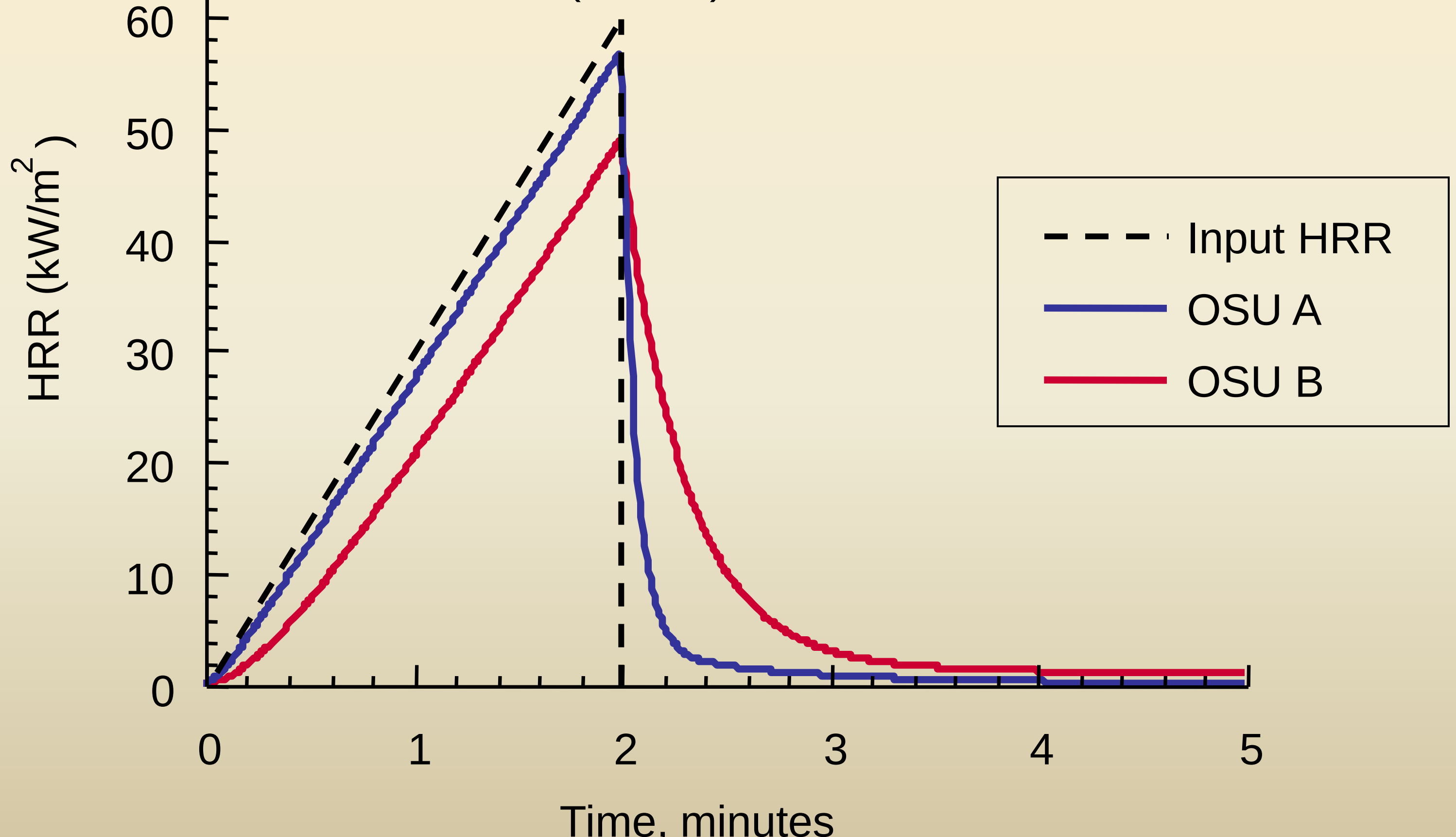
Apparatus Dynamics From Methane Calibration



Measured Apparatus Constants	OSU A	OSU B
Thermopile Response Time (τ_1)	0.07 min (4 sec)	0.3 min (18 sec)
Thermal Capacitance of Thermopile (C_1)	0.41 kW/mV	0.31 kW/mV
Inner Pyramidal Section Response Time (τ_2)	0.7 min (42 sec)	6 min (360 sec)
Thermal Capacitance of IPS (C_2)	4.7 kW/mV	1.7 kW/mV

OSU Dynamics Can Account for Reproducibility of TP Method

	Input	OSU A	OSU B	Reproducibility
2-min HR (kW-min/m^2)	**60**	**54**	**42**	± **20%**
PHRR (kW/m^2)	**60**	**57**	**49**	± **10%**



Conclusions

Removable oxygen consumption system and methodology demonstrated for 14 CFR 25 Heat Release Rate Apparatus (O2SU).

Effect of air flow on TP method largely accounted for by average temperature of mixed chamber and bypass air at thermopile.

Radiant heat exchange by smoke/soot is important for HRR by TP method but not for O2 method.

Air flow alone does not account for reproducibility of TP method. No systematic effect on HRR for bypass/chamber flow rate ratio, $s = 3 \pm 1$.

Apparatus dynamics may account for reproducibility (more work needed).